

Embedded Diagnostic/Prognostic Reasoning and Information Continuity for Improved Avionics Maintenance

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Abstract - The authors are developing enhanced onboard and at-wing diagnostic technologies applicable to both legacy and new avionics. The paper identifies onboard information sources and automated reasoning techniques that build upon existing Built-in-Test (BIT) results to improve fault isolation accuracy. Modular software and data elements that combine BIT with contextual information, component usage models, and novel reasoning techniques are described. In addition, the authors identify candidate avionics component applications to implement prognostics (prediction of impending problem) using forecasting techniques. A demonstration of diagnostic/prognostic prototype reasoners and information continuity using an open architecture framework within the streamlined maintenance concept is offered.

I. INTRODUCTION

Avionics systems are diverse, with developments spanning decades, but they can be broadly classified as legacy ‘federated’ and modular ‘integrated’ systems. Legacy avionics systems, comprised of many stand-alone replaceable units connected in a ‘federated’ architecture, are successful from a flight performance and functionality perspective but possess limitations for fault isolation and root cause diagnoses. Current statistics of cannot duplicate (CND) and no-fault-found (NFF) indicate the need for improvements. The design of newer, integrated, modular, backplane digital electronics provides a direct opportunity for better diagnostic and ambiguity reduction through a better understanding of system dependencies. Onboard and at-wing upgrades that include the capture and fusion of 1) operating conditions; 2) input and output parameter sets 3) environmental data; and 4) diagnostic and prognostic model results can provide significant benefits.

Current military avionics diagnostic and repair processes suffer a large degree of error [1,2]. CND, RTOK, NFF, or otherwise cannot verify (CNV) statistics range to as high as 50 to 75 percent [2]. The net result of this problem is a maintenance and logistics infrastructure that must sustain substantial overhead in order to support replacement of equipment that may not be faulty [3]. Another effect of this

loss of repair and maintenance accuracy is degraded overall mission readiness. The problem has been extensively studied and there exist many current attempts to mitigate errors in the process. These attempts range from the overall design and implementation of new ideas within future integrated avionics systems down to the incorporation of reconfigurable test suites for current and legacy avionics systems. Some enabling technologies include the development of an automated test meta-language (ATML) [4], the development of open systems automated test equipment through the Agile Rapid Global Combat Support (ARGCS) joint initiative [5], the implementation of sophisticated at wing systems stimulation [3], and the exploration of the feasibility of providing onboard embedded diagnostics for legacy avionics systems.

The authors are developing several technologies for enhanced onboard fault isolation and scenario recreation for offboard verification applicable to both broad classes of avionics. Specifically, the current paper identifies onboard information sources and automated reasoning techniques that build upon, but are not limited to, Built-in-Test (BIT) results. The specific diagnostic and prognostic modules are constructed using open system software architecture tenets, and a specific eXtensible Markup Language (XML) schema representation was adopted. This design provides greater flexibility within a platform application to place the reasoning at multiple levels in the diagnostic chain: onboard, at-wing, and remote depot. It also enables greater reusability across multiple platforms, which will reduce the need for totally dedicated software development or test equipment for each platform.

II. AVIONICS CLASSIFICATION

A. Legacy ‘Federated’ Systems

The term *federated*, used to describe traditional avionics, means each LRU is an independent unit possibly made by different manufacturers, and potentially, varying

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technology. Each manufacturer provides diagnostic capability for each LRU in the form of a built in test (BIT), automated test equipment (ATE), and test program sets (TPS). In addition, separate interactive electronic technical manuals (IETMs) may or may not be provided. All of the independent LRUs are expected to function side by side in a largely autonomous fashion to provide the total system functionality required to fulfill the aircraft's mission. It is this integration, albeit loose, and its potential system level effects that are not typically considered by the current maintenance infrastructure.

B. Modular 'Integrated' Systems

Integrated Modular Avionics (IMA) is an emerging design approach that seeks to maximize the benefits of system interconnectivity gained by providing common interfaces to components in the avionics systems. Military examples include the F-22 Advanced Tactical Fighter, the F-35 Joint Strike Fighter, and the RAH-66 Comanche helicopter. Many benefits are provided in these designs such as: system redundancy, situational awareness, real time diagnosis, and dynamic reconfiguration. In short, they are designed with more consideration of the overall system and its dynamics [5].

Integration is achieved through architectures ranging from

benign message passing on a bus, where the failure of one LRU simply means that results won't be completely accurate, to complete level integration where a global controller (software, hardware, or a combination of both) assembles all data for manipulation and display [3,5].

III. AVIONICS MAINTENANCE OPERATIONAL CONCEPT

A comprehensive diagnostic and prognostic capability for avionics system components builds upon enabling technologies such as built-in-test, advanced health monitoring algorithms, reliability and component aging models, prognostics methods, and knowledge discovery tools.

An overall operational concept is pictured in Figure 1. A paradigm shift from the onboard data capture to the logistical infrastructure will best maximize the opportunity presented by embedded avionics diagnostics and prognostics technologies being developed. The operational concept illustrates the streamlining of the three-tiered maintenance structure with system and component analysis occurring onboard and/or at-wing. This evolution, through a multi-step process, of current methods is supported throughout evolving vehicle health management (VHM) system framework. From more accurate at-wing diagnostics to the measurable enhancements that prognostics can

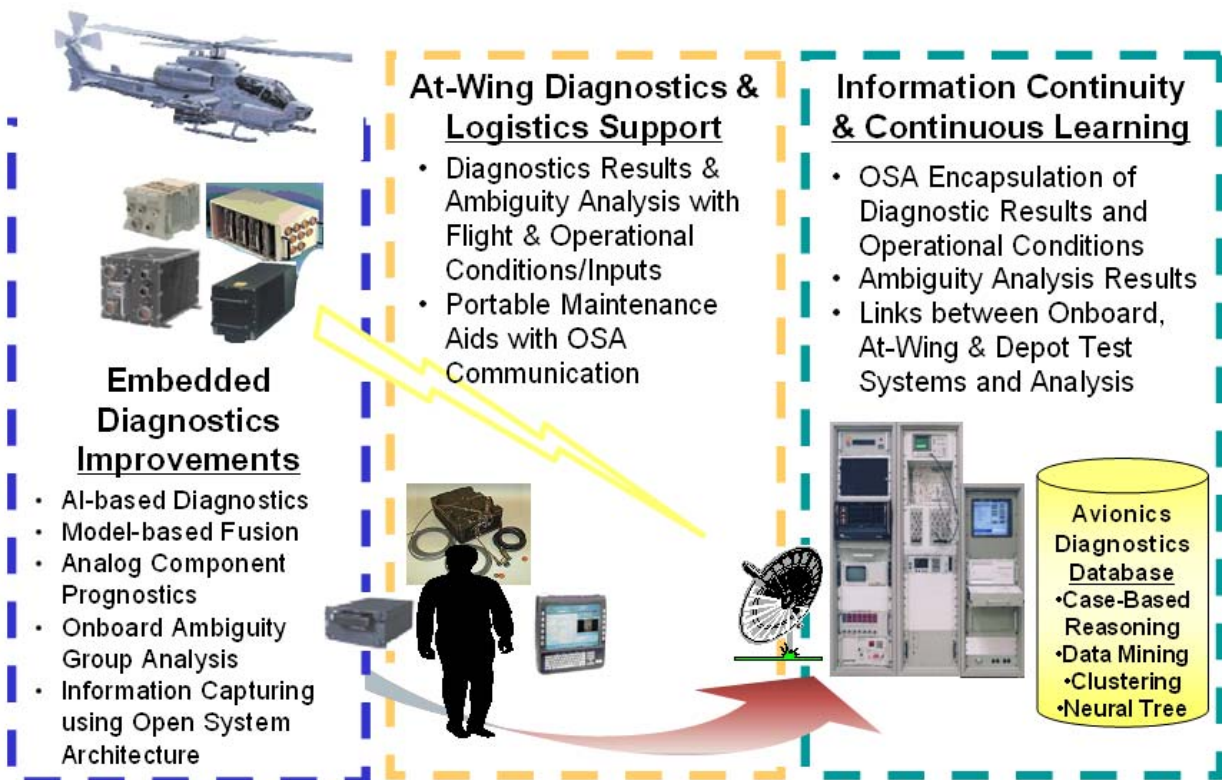


Figure 1 - Operational Concept for Embedded Diagnostics/Prognostics and Picture of Future Implementation

provide for the logistical support structure, the data driven architecture described here can serve as the foundation and core support to enable such a paradigm re-alignment. An “open data” architecture will be critical to ultimate deployment and acceptance.

This framework and vision is consistent with the onboard PHM (Prognostic and Health Management) as well as advanced Automated Test Equipment (ATE) approaches such as the Agile Rapid Global Combat Support (ARGCS) system. The future PHM designs will make optimal use of the predictive information using the autonomic logistics information system. The ARGCS goal of software interoperability will also be enabled by the open data architecture proposed to automatically recompile the TPS (Test Program Set) for different applications [5].

The field is diverse. Opportunities to integrate an embedded avionics PHM system are numerous. Some of the earliest opportunities may come in the arena of legacy system upgrades. Federated components operating together within an aircraft share many common bonds and can affect each other in ways that can be detected globally. Power systems, data busses, environmental factors, and wiring infrastructures are examples of some of these common bonds. The interactions among these factors create confounding issues to diagnostic systems that are not accounted for in LRU built-in-tests or at any other level of the maintenance infrastructure. From a global perspective this symbiotic “systems” relationship can provide a large opportunity to collect evidence that can be used to diagnose faults and predict failures. Rather than confounding, these relationships can be used to an avionics health management system’s advantage to lower the total life cycle cost (LCC) associated with the avionics system.

IV. ONBOARD EVIDENCE SOURCES

Impact, with the assistance of Honeywell, sought to identify data that could be used in the implementation of an on board avionics health management system and evaluate its evidentiary importance to the provision of a robust diagnosis and prognostic update. These factors will drive the implementation of the diagnostic/prognostic system. A detailed explanation of these evidence sources is given here.

A. Time Stamp

Correlation in time is the most obvious deficiency in the current federated avionics diagnostic approach. While length of operation, or time since the last event, may be available to the BIT, there is typically no absolute time record recorded. Valuable information regarding operational parameters, global system behavior, related component behavior, and myriad other possible related factors can best be correlated in true time. This time record allows the discovery of causal relations and thus, is imperative.

B. System Power

All electronic systems require stable power supplies that operate within regulated parameters. Operation outside these parameters for extended periods of time or even momentary, at extreme conditions, can cause premature failure of electronic components. In order for an effective prognostic system to be implemented, all major factors that will affect a component’s remaining useful life should be monitored. In addition to the prognostic forecasting capabilities provided by monitoring system power, multiple confounding errors by electronic components can, quite often, be correlated with global power problems.

C. Temperature of LRU/SRU

Thermal activity can be utilized as an indicator of LRU/SRU functionality and current health state. Electronic components have normal operating temperature ranges specified by the manufacturer. Operation outside of these ranges dictates a possible update of the component model regarding remaining useful life in order to provide accurate prognostic output. This also represents a stress to the system that can be accounted for using the model-based diagnostics and prognostics approaches.

D. Vibration LRU/SRU

Physical shock and excessive vibration are known to have detrimental effects on electronic equipment. These parameters should be monitored and exceedances recorded to provide input to the diagnostic reasoner or update the prognostic model. Failing cooling fans, oscillating transformers, loose and vibrating components, and other failures or precursors can be more readily identified.

E. Power LRU/SRU

Component power fluctuation that does not correlate with global system power anomalies can be used to indicate and pinpoint individual LRU/SRU failure as well as indicate possible wiring system problems. Correlation of local power anomalies at the LRU/SRU level can help pinpoint the source of wiring problems or other factors causing the anomaly.

F. BIT Error

Built-in-test error codes provide a data recording trigger as well as a starting point for problem diagnosis. It is quite likely that with correlation in time to all other sources of evidence, some number of BIT errors will be deemed spurious or caused by other external interactions. However, in the event of actual LRU/SRU failure, these errors remain as a key insight to the manufacturers design expectations through the associated BIT error logic.

G. Design Logic of BIT Errors

Design criteria are used to set an actual BIT error. In order for the error message to be activated, certain conditions have been met for certain periods of time. These conditions and thresholds can serve as evidence that

provides a higher order understanding of events at the system level.

H. LRU Analog Inputs

Many legacy systems use various analog inputs to controllers. The inputs noise level existing on these may or may not be monitored by BIT. In the case that it is not, monitoring and low-level reasoning is appropriate to provide more detail level inputs to the VHM system.

I. LRU/SRU Reliability

Component lifing data begins with the reliability data provided by the design engineer and is further refined through reliability growth models developed during a system's lifetime. This data serves as a basis for the construction and maintenance of individualized component models that are then updated to account for local exceedances. While probability models cannot describe discrete cases, they can be used to provide predictions of remaining useful life and assess confidence values to diagnostic/prognostic outputs.

J. LRU/SRU Life History

An LRU/SRU can be tracked throughout its initial installation and life history as it is migrated from system to system through failures and repair within the logistics apparatus. Such tracking can detect rogue units, provide accurate update date to component life models and assist in the development of a repair effectiveness tracking system.

K. LRU/SRU Logistics Considerations

The diagnostic output will be a ranked list of maintenance actions. The intelligent maintenance system will also consider the available spares and equipment required to

further prioritize a timely repair.

These evidence sources comprise the fundamental basis for a robust diagnostic and prognostic health management system. This basis is used to derive specific design solutions for embedded avionics to affect positive impact to the current maintenance system. Methods to capture such data in an open format to enable greater portability are addressed next.

V. INFORMATION TRANSFORMATION AND DATA CONTINUITY

Openness is a general concept that denotes free and unconstrained sharing of information. In its broadest interpretation, the term "open systems" applies to a systems design approach that facilitates the integration and interchangeability of components from a variety of sources. For a particular system integration task, an open systems approach requires a set of public component interface standards and may also require a separate set of public specifications for the functional behavior of the components. The underlying standards of an open system may result from the activities of a standards organization (e.g. IEEE), an industry consortium team (e.g. OSA-CBM), or may be the result of market domination by particular product (or product architecture).

An open system approach to automated diagnostics/prognostics begins with a functional decomposition of the various evidence/data sources and dissection of the logical points for system data exchange. The goal is to describe a system architecture that permits the access by many diverse component/software suppliers to all aspects of the system. This must be done in a manner that

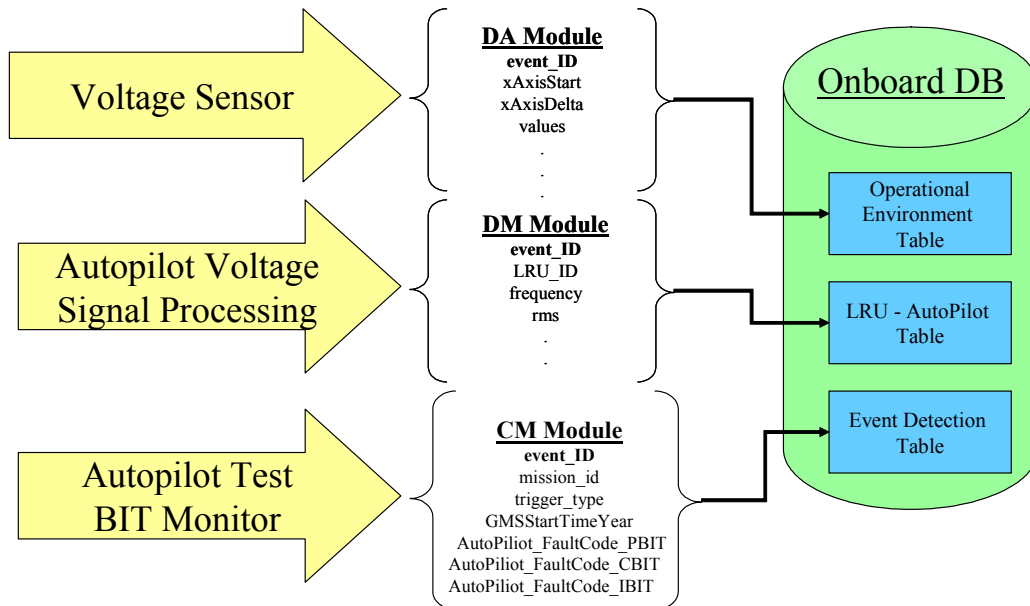


Figure 2 - XML Data Insertion to Database

does not constrain the performance of the prognostics health management system. The end result should be defined system output formats, software module input formats, and minimal set of performance specifications.

Impact Technologies explored and demonstrated open information exchange between onboard hardware, various available off-board data sources, and various avionics health management (AHM) software components. An open data architecture facilitates information continuity throughout the onboard and off-board AHM system by encapsulating a standard of what information (system id, sensor/LRU/SRU information, data collection parameters, etc.) will be represented by the information stream and a standardized meta-data description of what the individual data elements represent. Two examples of open systems approaches are AI-ESTATE and OSA-CBM. Automatic Test Meta Language (ATML) committee of IEEE is exploring the development of an XML standard for automated test equipment (ATE). Currently available OSA-CBM protocols describe an open standard for data collection, condition monitoring, and maintenance information exchange.

The research team chose OSA-CBM as the model for a prototype implementation due to the diverse experience that Impact Technologies has accrued with design and implementation of VHM systems based on this protocol. OSA-CBM describes the exchange of information from data collection to data manipulation as well as diagnostic reasoning and health assessment. Modalities described by OSA-CBM include XML, CORBA, and COM/DCOM [7]. Impact chose to implement the prototype demonstration using XML data streams due to the illustrative mapping of meta-data (header tags) to database fields.

An OSA-CBM wrapper provides a means for any data

stream to be wrapped in XML and sent to another module. The wrapper will be in a standard OSA-CBM format. This standard will allow the data to be sent to a new module and easily parsed by an XML wrapper program. Neither module needs to know what the other is doing. The only requirement is that both modules can parse XML. Several open-source programs, such as Jame's Clark's expat and the DOM parser, exist, and could be used as an efficient way to parse the OSA-CBM wrapper [8]. Application of the OSA-CBM wrapper technique to data streams, allows for a modular program design with an ease of interchanging modules from different sources.

Output from many available data capture and reasoner routines, e.g. BIT and BUS monitors, is not likely to be found in an OSA format specified by an interchange schema. An OSA wrapper uses local translation knowledge of the data output format from these individual sources to convert the stream to verifiable OSA stream [7]. To create XML output that conforms to a schema, the wrapper will employ handlers (Handlers are program modules that enable the schema cross validation [8].) to interpret the incoming data stream and provide the XML tags and appropriate structure. A wrapper makes no change to the existing software, but provides the output standardization that preserves situational context and supports information continuity.

VI. AUTOMATED REASONING TECHNIQUES

A. Bayesian Belief Network (Nodal Model)

Impact constructed a Bayesian Belief Network (BBN) to illustrate a top-level system reasoner within an avionics

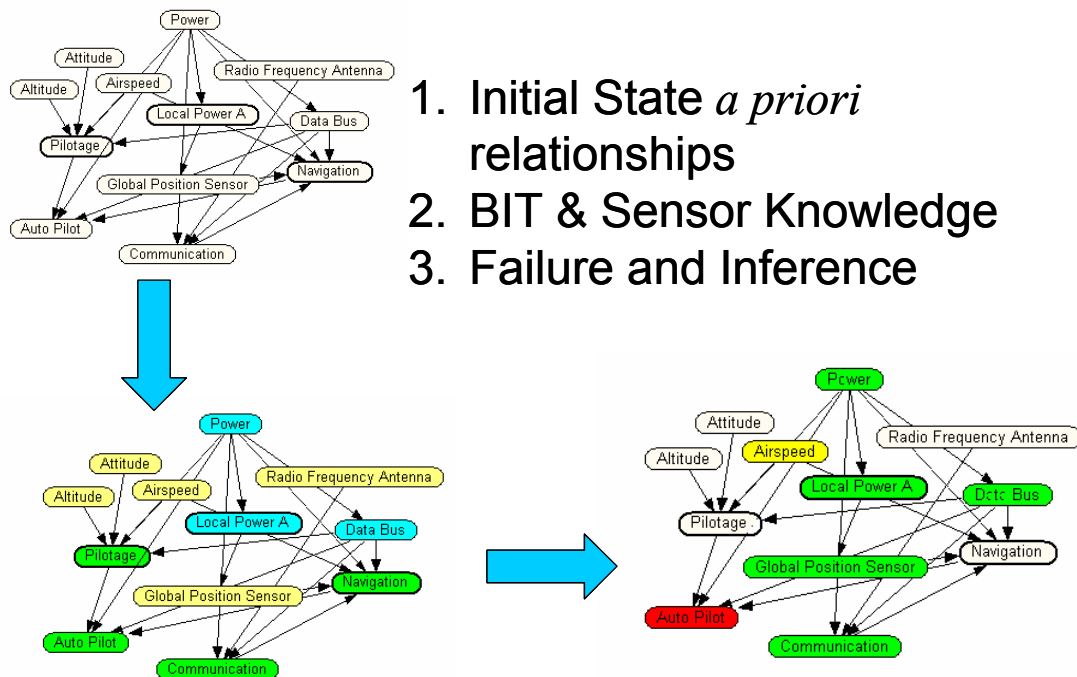


Figure 3 - High-level reasoning using a Bayesian Network

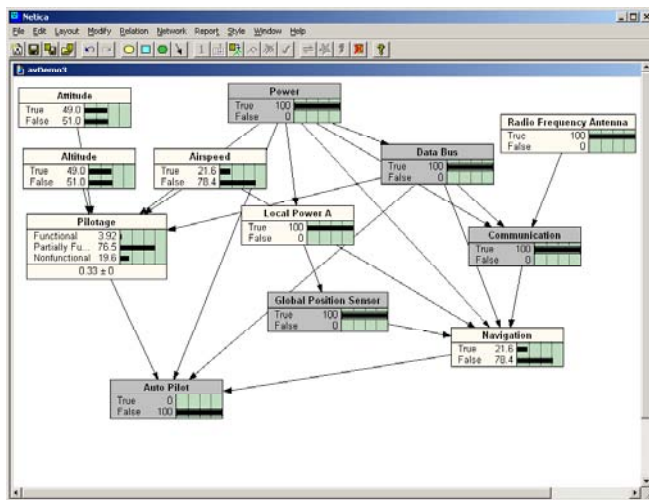


Figure 4 – Netica BBN (Airspeed Sensor Example)

VHM system. Several Bayesian Belief Network tools are available. Impact used Netica™ to demonstrate feasibility by designing a prototype nodal system to describe a basic avionics system. The example system contains four major LRUs and several existing avionics input units. The BBN, see Figure 3, describes the relationships and dependencies contained within the system.

Autopilot, navigation, communications, and pilotage are the four major LRUs represented by the BBN in Figure 4. A communications data bus, main system power with one additional sub-circuit, a radio frequency antenna, global position sensor, and altitude, attitude, and airspeed sensors are included as inputs to the system. The arrows and associated truth tables describe relationships and dependencies. For example, the radio frequency antenna, a root node, is assigned a 50/50 *a priori* probability of functioning. This represents no system design reliability knowledge, a point worth keeping in mind. A portion of the communications node truth table is dedicated to the representation of the cause and effect relationship it has with the antenna. The key to robust utility of the BBN is the initial non-representation of design reliability knowledge at the nodes. This representation can come later as a part of a low-level reasoning process that uses evidence to set belief values at each node when and if adequate evidence becomes available.

B. Evidence-Based, At Wing Reasoning Process

Positive and Negative Evidence, along with Real Fault Probabilities and False Alarm Rates contribute to the Failure Mode Ranking process. Positive Evidence is defined as collaborative indications (LRU status or signal status) that directly indicate failure modes. Negative Evidence is defined as the absence of evidence when it is expected.

Figures 5 and 6 present the use of the at wing reasoner for ambiguity reduction. In the first figure are the results of the

onboard embedded diagnostics. These results have left an ambiguous diagnosis where four LRUs compete for ranking as the probable cause of the failure. The at wing reasoner will use this embedded diagnosis as an input and, with knowledge of additional testing that can be completed, will suggest an optimal path for ambiguity reduction. The output after evaluating the test performed and resultant clarification

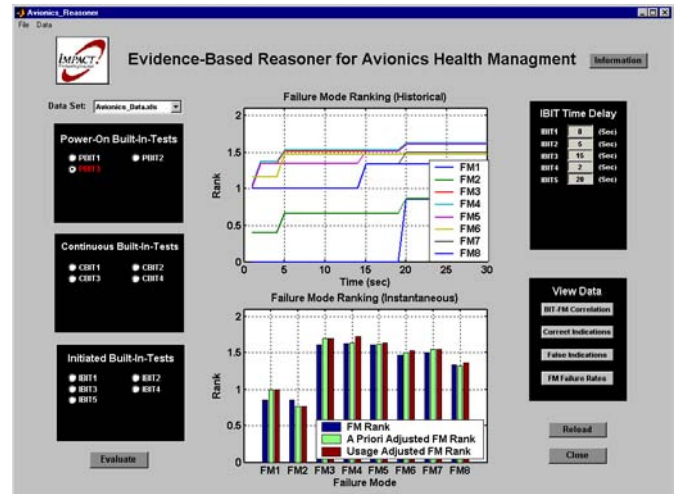


Figure 5 – At wing Reasoning: Initial Ambiguity State

is illustrated in the second figure.

The use of this at wing reasoner with LRU self-test enhanced by at wing stimulation is one major step in the reduction of ambiguities that occur at wing. These ambiguities typically result in the pull-and-replacement of two or three LRUs. Implementation of such a process at wing can yield an obvious large reduction process error by elimination of the pull-and-replace repair process that is currently executed. The recent evolution of synthetic

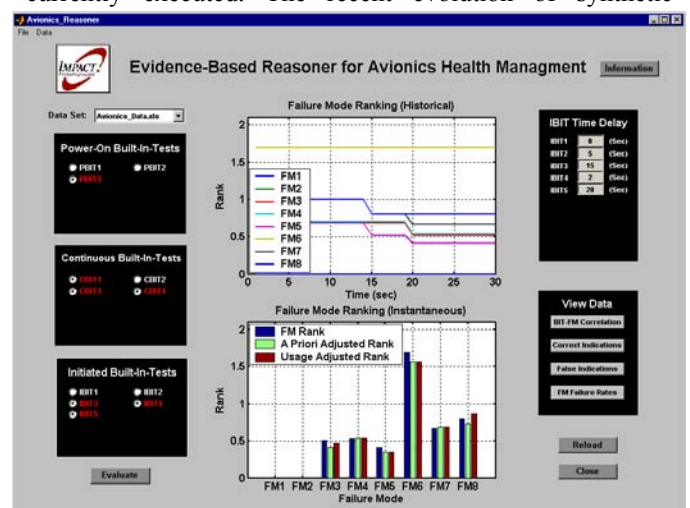


Figure 6 – At Wing Reasoning after Correct Tests

instrumentation packaged within MIL-STD_28800 Class 1 specs will facilitate more testing and diagnosis at the wing and/or forward echelons.

VII. LEGACY AVIONICS IMPLEMENTATION PROTOTYPE

For the purpose of demonstration of the open data approach and reasoner functioning, Impact developed a prototype implementation using a Honeywell (C-130) Autopilot. The C-130 autopilot is a prime example of legacy system with analog and digital inputs operating in a federated architecture. There exists limited diagnostic modeling, and the C-130 autopilot has highly developed BIT. Moreover, the autopilot touches many aspects of the avionics system and gives a good system level perspective.

Within the demonstration, the autopilot is connected to a laptop computer via a MIL-1553 interface. Impact demonstrated the capture of BIT and fault code information, its open information exchange conversion, and its subsequent synthesis and processing of as would be capable onboard or at-wing.

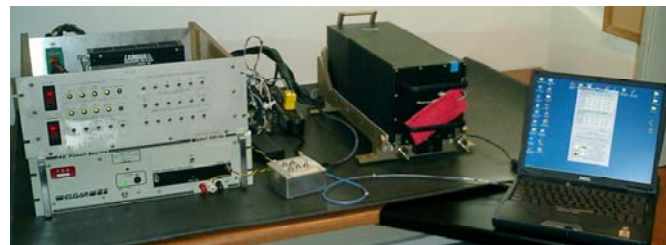


Figure 7 – Demonstration Setup

Impact wrote an OSA wrapper to translate the proprietary hexadecimal stream of words into an OSA data representation. Figure 8 is a screen-capture of the data extraction and conversion module developed by Impact Technologies to demonstrate onboard data capture to off-board availability and continuity. In the module, AACP (Aircraft Flight Control Processor) data is received via the C executable. The raw, hexadecimal data is converted to an XML data stream, which conforms to a condition monitor output specification defined by the OSA-CBM protocol version 1.0.2. This module communicates on the 1553 data bus using a PCMCIA card provided by Ballard Technology. Ballard provides a C application programmer’s interface (API) that was incorporated into Impact’s module. The GUI implementation was developed with TCL/Tk (Tool Command Language). The XML document can then be viewed using an Internet web browser.

Impact developed a Java based simulation of the evidence processing and reasoning portion of the AHM system. illustrates the flow of evidence from the open database through a data broker interface to various low level evidence reasoners. Results are then routed to a Bayesian Belief Network, Neural Fuzzy system and a Dempster-Shafer fusion module that complete the system level

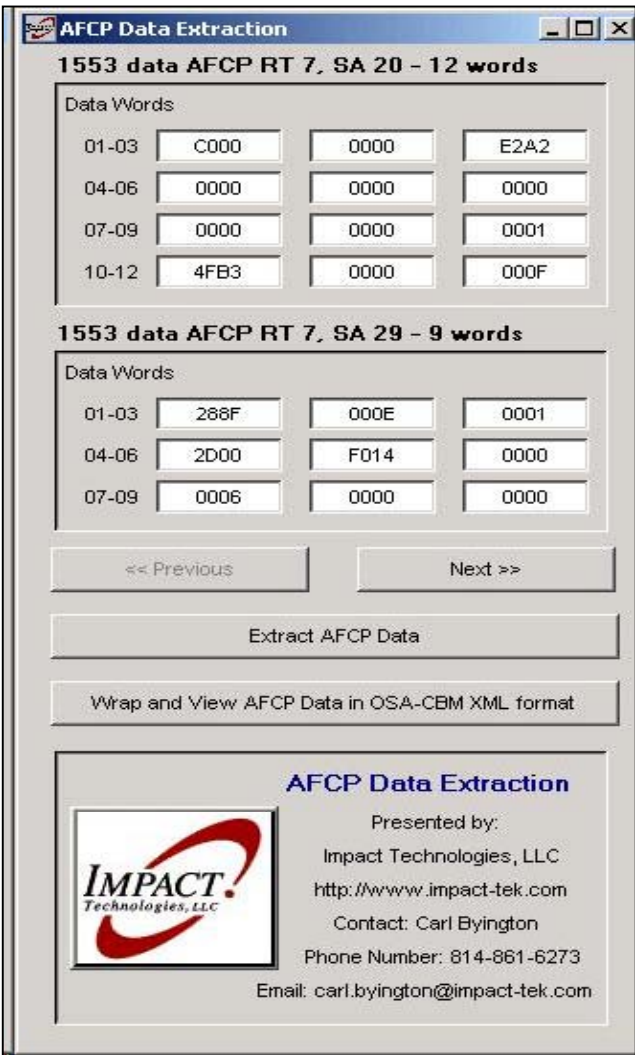


Figure 8 - Impact 1553 data extraction and XML translation module

reasoning process. A maintenance report is output, along with updates to system usage models and reliability models as necessary. A description of three scenarios used to exercise the system is presented below.

Scenario 1 describes an event where the autopilot disengages, due to an air speed sensor malfunction, and sets a BIT error. In the case of the C-130 autopilot, the air speed sensor data is an input from the ARINC 429 data bus. The BIT error would only indicate that there was a problem with the 429 interface. This indication could resolve to numerous possible root causes, ranging from the actual sensor problem to an internal interface problem within the autopilot. A system level reasoner can capture the knowledge that the data bus is working, power is good, communications is working, the global positioning system is working, etc., and ultimately resolve the root cause to a malfunctioning air speed indicator to a confidence of above 80%.

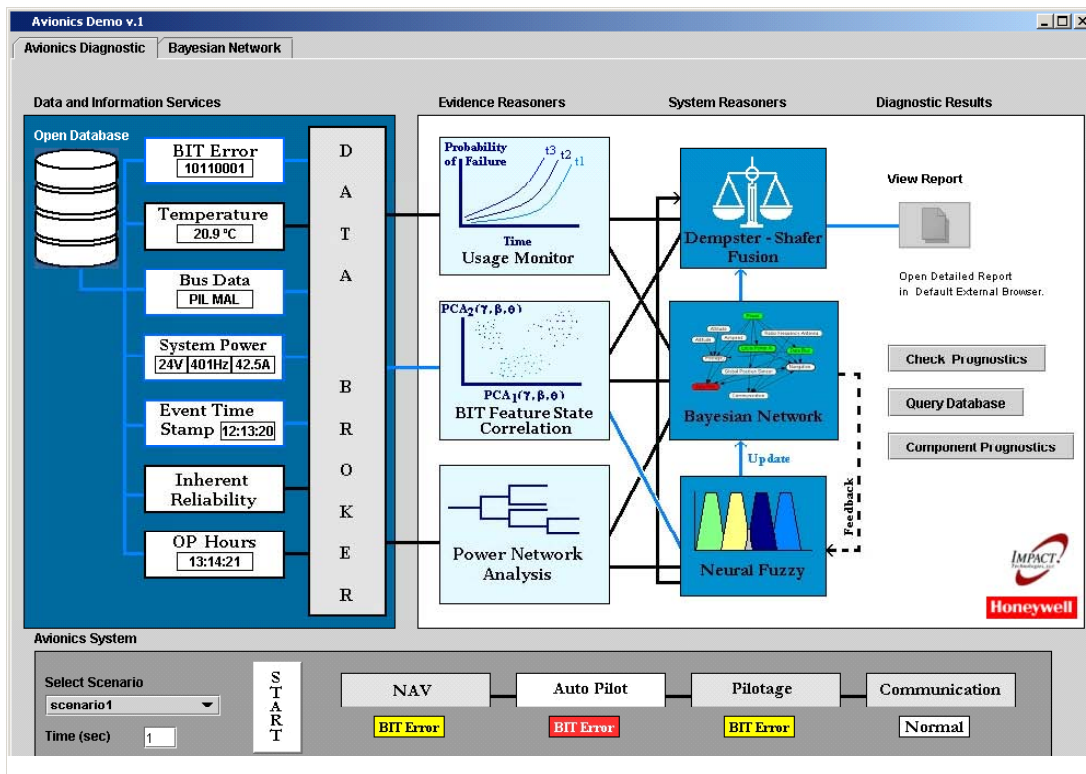


Figure 9 – Embedded Avionics Concept Demonstration

VIII. PROGNOSTICS CONSIDERATIONS

There fundamentally exist four problem types within avionics systems (see Figure). Binary faults produce very short time horizon progression from operational to failed. Intermittent problems can be either repeatable with conditions and operational modes or nearly random. Class 4 problems are those that possess more gentle progression rates.

Prognostic features within the embedded avionics system include:

- Specific component prognostics using sub-circuit component model ("weakest link")
- Health state tracking for graceful degradation (Problem Type 4)
- Fault identification diagnostics with association to known effects

Outputs from the avionics prognostics module will be useful throughout the maintenance and logistics system. Model based diagnostics/prognostics update, logistical planning, and evaluation metrics are the major users of the outputs of the prognostics system. The outputs of a prognostic system will take the form of :

- Time to Failure with associated confidence.
- Remaining Useful Life or operational cycles with associated confidence.
- Failure Risk with associated confidence.
- Time to Specific Maintenance Action.

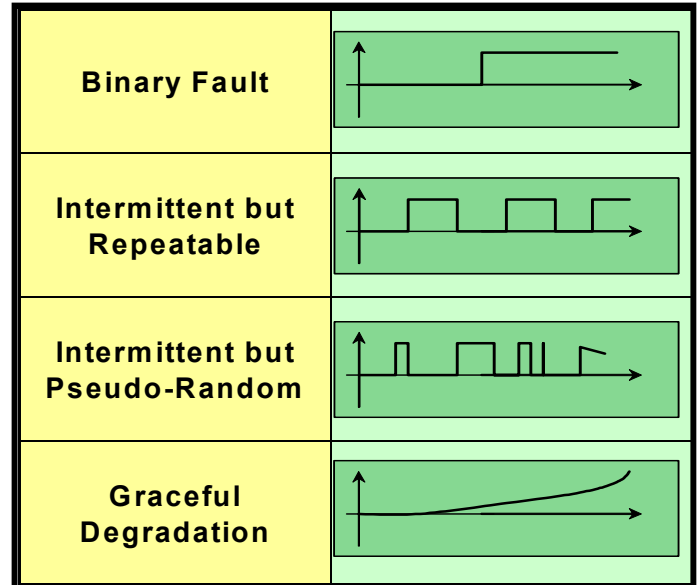


Figure 10 – Avionics Problem Classes and Class 4 for Prognostics

IX. SUMMARY AND FUTURE WORK

Impact identified evidence sources and developed reasoners with open data interfaces specific to avionics health management and related the use of such within a streamlined maintenance operational concept. Several prototypes were developed that could be further implemented to address specific diagnostic activities.

Impact and Honeywell are currently planning a more detailed Phase II effort with specific implementation of some of the prototypes discussed in this paper. Specifically, there exists the potential for a generic system reasoner to be developed using a Bayesian or Dempster-Shafer approach. The Evidence-based Reasoner includes the means to adjust the FM rank based upon multiple sources including failure rates, usage, and technician input. The open data architecture also allows Impact the opportunity to generate OSA wrappers for both legacy and new systems.

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